ANALOG DEVICES

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Versatile Transmitter Chip Links Strain Gauges and RTDs to Current Loop

by Paul Brokaw

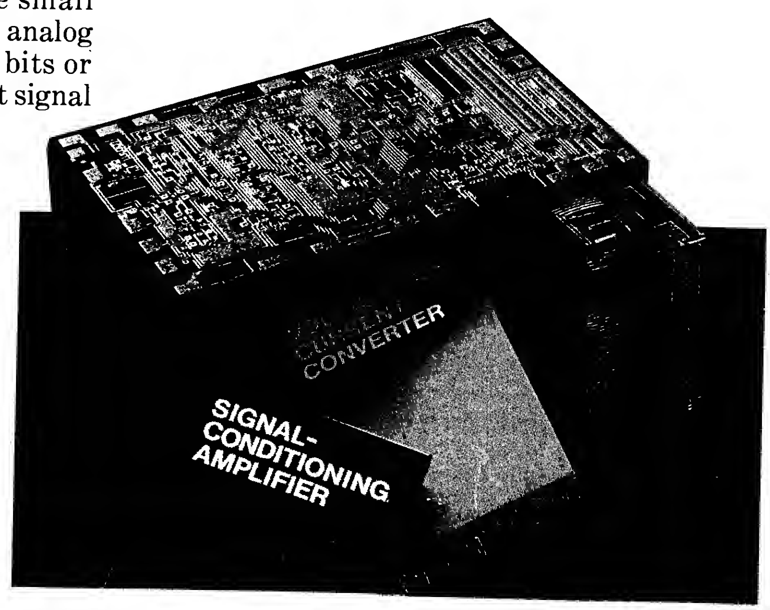
Replacing a board full of parts, a transmitter chip can be configured to match the 4-to-20-mA loop to a range of different process-control requirements.

The digital transmission of data may seem to be taking over from analog transmission. But in the process-control arena, the two-wire 4-to-20 mA current loop remains firmly entrenched as the traditional connection between transducer and control room. Moreover, that holds true even though converting the signal of a resistance temperature detector or resistive bridge into 4 to 20 mA demands about the same number of components as converting it into an 8- or 10-bit serial digital word.

In both cases, the same types of operations must be performed. The transducer must be excited, the signals conditioned, and the small floating voltages amplified. In addition, analog input voltages must be converted into bits or current, in the process creating an output signal that can drive a two-wire line several miles long. Also, that line must carry the circuit power.

The arrival of the AD693 process-control transmitter goes a long way toward guaranteeing the staying power of the 4-to-20-mA current loop. The chip tackles all the functions required to handle standard resistive transducers and to operate from and determine the current in a typical process-control loop. In addition, pin strapping enables the chip to work with other current ranges, and a few extra passive parts permit its use with a broad selection of sensors.

As important, it can replace the pc boards, modules, and hybrids now taking care of those functions. Consider that a pc board is a relatively large unit whose many ICs, transistors, and passive and adjustable components dictate careful design and expensive assembly, calibration, and testing measures. Modules eliminate those



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concerns (apart from calibration) without necessarily reducing time and cost. Hybrids are small, but present problems of performance, functional completeness, and cost.

In sharp contrast, the 20-pin AD693 transmitter IC is an accurate, versatile, and tiny part that alleviates worries about functions or cost. Its precision reference sets the 4-mA zero point and also can excite a sensor. In fact, the chip's bag of signal-conditioning tricks covers virtually all common resistive sensors.

Loop-the-loop

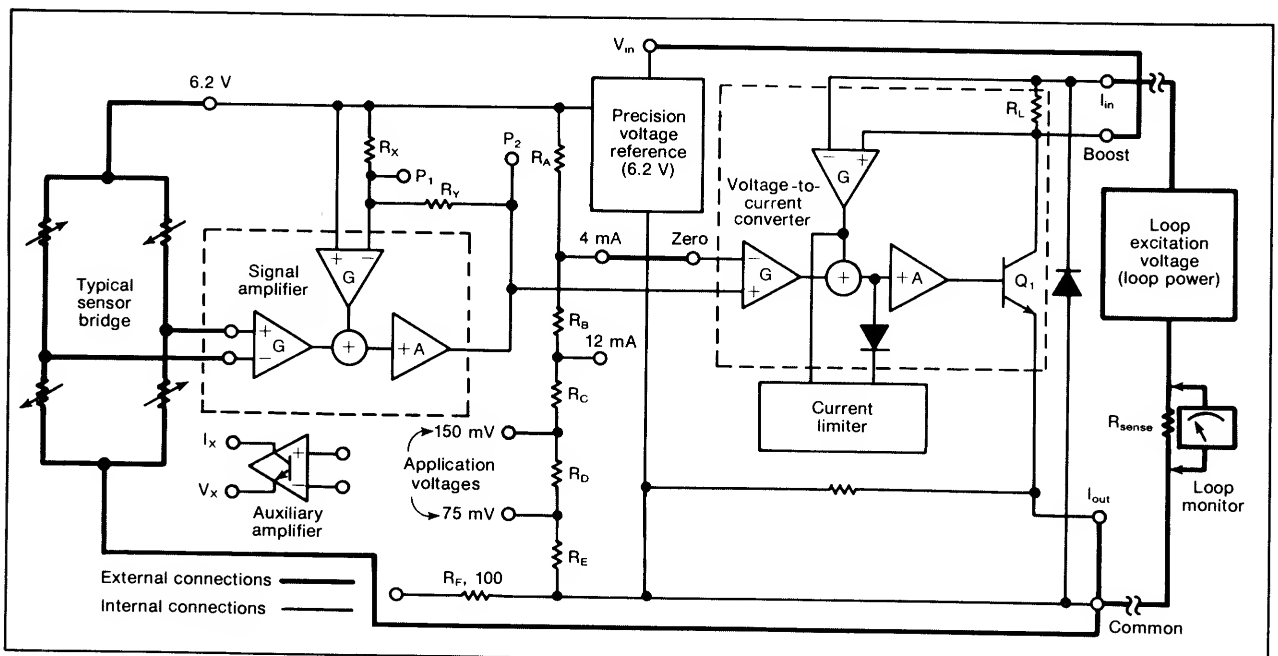
The transmitter's operation is best demonstrated when its inputs are connected to a resistive bridge transducer and its output and power source to a 4-to-20-mA current loop (Fig. 1).

The loop is powered by a voltage source in series with a current-sensing, or current-monitoring, resistor, R_{sense}, located at the receiving end in the control room. The voltage across R_{sense} is the high-level signal to the controller. The AD693 connects to the two-wire loop at its remote end and couples it to the measurement represented by the output of the bridge transducer, or the sensor.

The reference on chip excites the bridge, the output of which connects directly to the chip's signal amplifier. That amplifier is an instrumentation-type circuit with a differential input and a single-ended output, relative not to ground but to the 6.2-V reference line. The output of the signal amplifier drives a voltage-to-current converter, which measures the total loop currrent with the voltage drop across the loop's sampling resistor, R_L. In turn it sets the loop's current, so that the voltage across R_L equals the input to the converter.

When a measurement unbalances the bridge, putting a small voltage at the input to the signal amplifier, the amplifier's output drives the converter's input positive, increasing the loop current. The gains of the signal amplifier and the resistance of the output resistor are laser-trimmed; in combination, they provide a pre-calibrated sensitivity relating the loop current directly to the bridge's output voltage. In addition, a current-limiting circuit monitors the current, so that if the input to the converter is overdriven, loop current is limited to 25 mA, protecting both loop and transmitter chip.

The zero input pin of the voltage-to-current converter is referred to a voltage that, because of the voltage drop across R_A, is slightly nega-



1. A one-chip transmitter, the AD693 converts the output voltage from resistive bridge sensors into a 4-to-20-mA process-control signal. Moreover, the chip excites the sensor, runs off loop power, and for many standard sensors, requires no span or zero trimming components.

tive with respect to the 6.2-V reference. So when the input signal from the bridge is zero, the converter's input is not zero and its output is 4 mA.

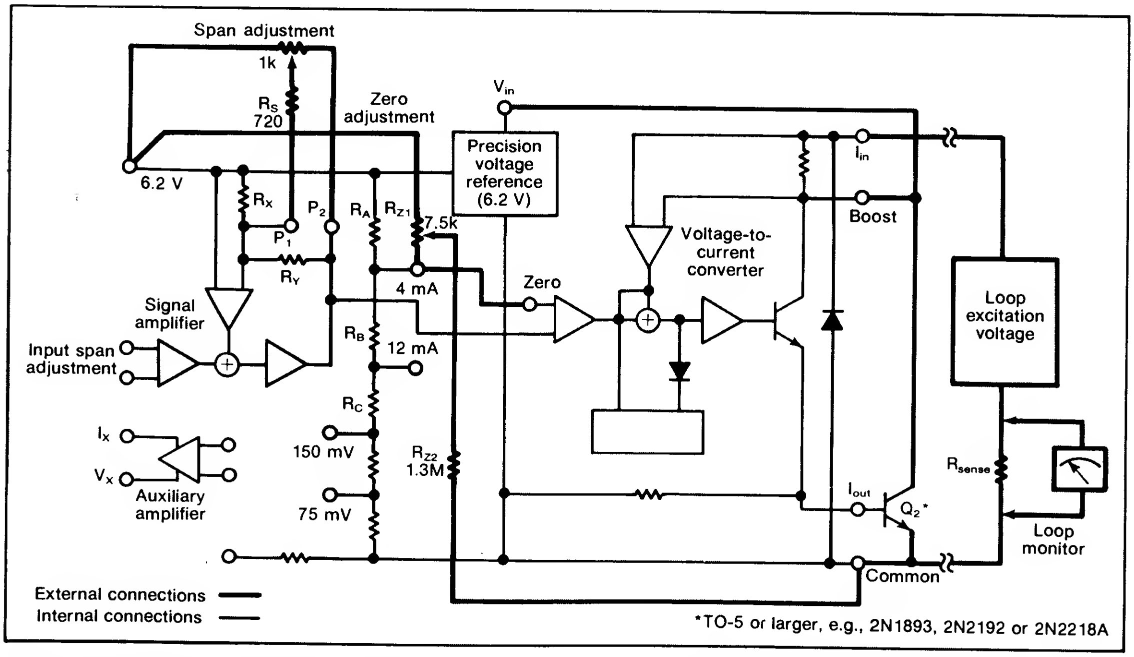
A voltage divider (R_A through R_E) from 6.2 V to common, or ground, is laser-trimmed so that connecting the converter's zero input to the divider's 4-mA tap results in 4 mA of loop current. Since that voltage is produced by a resistive divider, it can be easily adjusted to accommodate zero offsets in the bridge sensor. Moreover, the adjustment does not affect the signal amplifier's gain and thus is independent of the zero to full-scale range, or span.

An alternative connection for the converter's zero pin sets the loop current to 12 mA when the input is zero, meaning that input signals of both polarities can be handled. The zero pin also can be returned to the 6.2-V reference line, thereby reducing loop current to zero. That connection permits the chip to operate as a 0-to-20-mA converter, so long as the voltage reference and amplifiers are not powered from the loop. For most applications, the transmitter chip runs off loop power through the connection between the Boost pin and the V_{in} pin.

Connections between pins P_1, P_2, and the 6.2-V reference line provide the signal amplifier's negative feedback and take care of span adjustments. For instance, when the signal amplifier's gain is 2 (Fig. 1 again), the input span—that is, the signal that changes the loop current from 4 to 20 mA—is 30 mV. Connecting P_1 to P_2 changes the gain to 1 and the span to 60 mV; the span can be adjusted to a few millivolts by placing a resistor between P_1 and either P_2 or 6.2 V.

The way in which the input signal amplifier is designed produces a high differential input impedance and a wide common-mode range. The amplifier accommodates signals between 0 V and the 6.2-V reference and even, in some applications, signals greater than 6.2 V. The common-mode input range extends from −100 mV to within 4 V of the potential at V_{in}. The transmitter's ability to handle small negative voltages is valuable when ground-referenced signals have a small negative component. The positive range is useful when measurements are not powered directly by the reference.

The auxiliary amplifier solves a variety of excitation and measurement problems. For example, with the addition of two resistors, it operates at a noninverting gain of 10/6.2, which amplifies the reference, providing a low-impedance, 10-V source that can supply up to 3 mA to sensors.



2. The transmitter chip adapts readily to the addition of zero and span adjustment potentiometers when used with nonstandard sensors. Incidentally, when an external transistor, Q_2, handles the loop current, the chip can operate at 50 mA full scale.

Industrial Electronics: Versatile transmitter chip

When the auxiliary amplifier is used as a voltage amplifier, the output stage must be powered by connecting the I_X terminal to a positive voltage, such as the 6.2-V line or V_{in}. In this case, the stage takes current from the boost terminal (see Fig. 1 again).

This amplifier can be used in most noninverting configurations and has the same common-mode range as the signal amplifier. The voltage divider, R_A through R_E, has 75- and 150-mV output taps that, when used with the auxiliary amplifier and the internal 100-Ω resistor, can form a signal-conditioning circuit with six precalibrated ranges for RTDs.

Exciting currents

The auxiliary amplifier also has a feature that proves useful for the current-mode, or constant-current, excitation of sensors. Since the I_X terminal supplies all of the auxiliary amplifier's output load current, it can be used as a high-impedance current source. When configured as a voltage follower, driving the 100-Ω resistor and connected to either the 75- or 150-mV pin, it makes a 750- or 1500-μA constant current available for sensor excitation.

The chip's I_{out} pin supplies the voltage-to-current converter with the excess current—beyond the operating and excitation currents—necessary to create the proper signal current for the loop. In many applications I_{out} is connected directly to common.

The pin also can be used to overcome the one disadvantage of a monolithic transmitter—its limited power dissipation. Though the AD693's power devices dissipate up to 7.5 W, most of that power can be offloaded to a discrete transistor. That setup minimizes errors due to self-heating and extends the temperature operating range.

If a resistor of about 5 Ω is placed in parallel with the loop's sampling resistor, R_L, the chip can be tweaked to operate in a 10-to-50-mA current loop. That configuration makes it desirable to use an external transistor, which enables the chip to work over the full industrial temperature range (Fig. 2).

In that circuit, I_{out} drives the base of a discrete npn transistor, Q_2, which pulls current out of the Boost pin and delivers it to common. The external transistor is in effect Darlington-connected to the normal pass device, Q_1. As a result I_{out} supplies only the base drive for Q_2, which handles most of the circuit's dissipation. The external transistor works with 4 to 20 and 0 to 20 mA and with any signal-conditioning circuits.

Essential to the AD693 and any other signal-conditioning circuit is the ability to adjust zero and the full-scale range. User-selected options afford three choices of loop current for an input signal of zero: 30 and 60 mV at 4 to 20 mA; ±15 and ±30 mV at 4 to 20 mA; and 37.5 and 75 mV at 0 to 20 mA. (In the last of those, the zero pin is tied to 6.2 V.) Although these values are laser-trimmed for high accuracy, they may require adjustment to accommodate variability between sensors or to add ranges. The circuit of Figure 2 indicates an optimum technique for adjusting zero and span for the AD693.

Voltages of 15 and 45 mV, negative with respect to the 6.2-V line, set the 4-mA and 12-mA operating points from a nominal source impedance of 450 Ω. The zero adjustment circuit is constructed by adding external resistors to modify the internal voltage divider to drive the zero pin.

To find the proper resistor values, the desired range of output current, I_A, is selected and substituted in a series of equations. For instance, to adjust the 4-mA tap, the equation to be used is:

$$\text{Potentiometer } R_{Z1} = (1.6\ \text{V}/I_A) - 400\ \Omega$$

Then the series resistor would be evaluated as:

$$R_{Z2} = R_{Z1}\,(3.1\ \text{V})/[15\ \text{mV} + (3.75\ \Omega)(I_A)]$$

Similarly, for a divider connected to the 12-mA tap, the equations to be used are:

$$R_{Z1} = (4.8\ \text{V}/I_A) - 400\ \Omega, \text{ and}$$
$$R_{Z2} = R_{Z1}\,(3.1\ \text{V})/[45\ \text{mV} + (3.75\ \Omega)(I_A)]$$

These equations take into account the ±10% tolerance of tap resistance and ensure a minimum adjustment range of I_A. For example, selecting an I_A of 200 μA delivers a zero adjustment range of ±1% over the 20-mA span. At the 4-mA tap, then:

$$R_{Z1} = 1.6\ \text{V}/200\ \mu\text{A-}400\ \Omega = 7.6\ \text{k}\Omega, \text{ and}$$
$$R_{Z2} = 7.6\ \text{k}\Omega\,(3.1\ \text{V})/[15\ \text{mV} + (200\ \mu\text{A})(3.75\ \Omega)] = 1.49\ \text{M}\Omega$$

These resistance values can be rounded off to a convenient 7.5 kΩ and 1.3 MΩ, providing an ad-

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justment range slightly in excess of ±200 μA.

The full-scale range is adjusted by controlling the feedback around the signal amplifier, achieved by paralleling internal resistor R_X or R_Y with an external resistor. (The internal resistors are laser-trimmed in ratio rather than in absolute value, but they are within ±10% of their nominal value of 800 Ω.)

Padding spans

To create a span, S_1, of less than 30 mV requires calculating the value of resistor R_{S1} located between P_1 and 6.2 V in parallel with R_X, according to the equation:

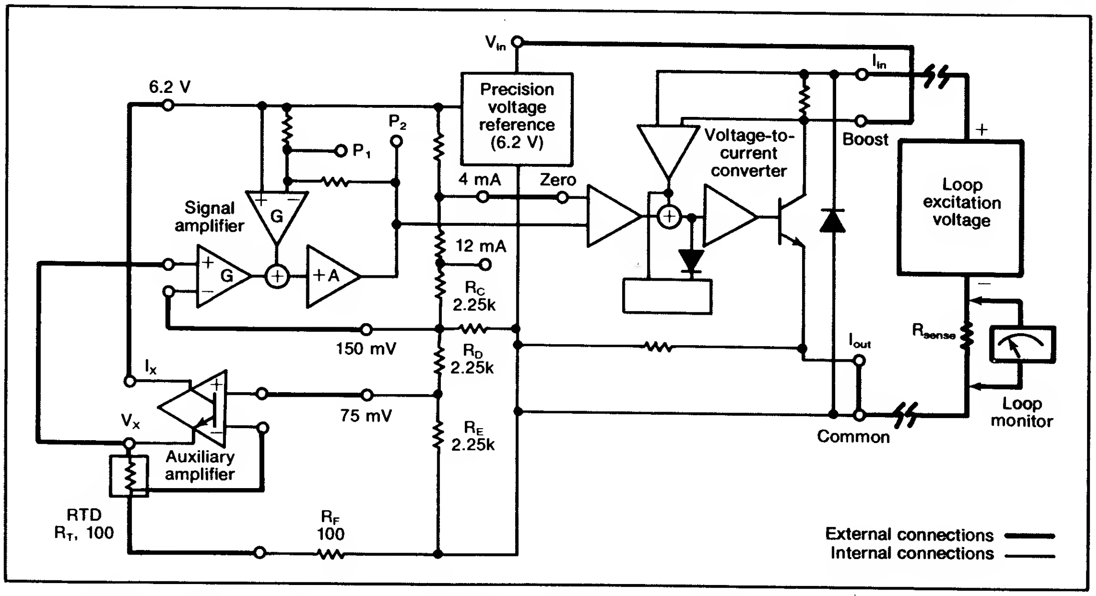
$$R_{S1} = 360\,\Omega/[(30\,\text{mV}/S_1)-1]$$

To set a span S_2 between 30 and 60 mV, a value must be calculated for resistor R_{S2} located between P_1 and P_2 in parallel with R_Y, according to the equation:

$$R_{S2} = 360\,\Omega/(1-60\,\text{mV}/S_2)/[(30\,\text{mV}/S_2)-1]$$

These are minimum values, and the resistors can be padded to obtain a particular gain; otherwise the circuit values in Figure 2 can be used with either R_{S1} or R_{S2} to get a range of span adjustments. For example, for continuous span adjustment between 20 and 40 mV, the 20-mV limit would be used to calculate RS_1 and the 40-mV limit to calculate RS_2, yielding the same value, 720 Ω. In this case the values happen to be equal, but in general, using the lower of the two values (R_S in Fig. 2) with a 1-kΩ potentiometer produces an adjustment range that encompasses at least the desired span.

Though that method of adjustment works



3. A complete loop-powered RTD measurement with six precalibrated ranges can be obtained with the AD693. Its auxiliary amplifier excites a dynamic bridge formed by the RTD, R_T, and the application resistors.

Temperature ranges (°C) for a 4-to-20-mA span with the AD693 and an RTD*

Input span	P_1 and P_2	Zero pin connected to 6.2-V pin	Zero pin connected to 4-mA pin	Zero pin connected to 12-mA pin
30 mV	Not connected	+25.9 to +130.5	0 to +103.9	−50.8 to +51.6
60 mV	Connected	+51.6 to +266.4	0 to +211.3	−100.6 to +103.9

*α = 0.00385 for a 100-Ω platinum RTD

well, the span of the AD693 can be adjusted with any scheme that is compatible with the built-in feedback network, as long as the amplifier is not overloaded. The network can also be used to inject currents, producing offsets or other additions to the signal applied to the voltage-to-current converter.

The excitation and signal-conditioning features of the chip easily adapt to measurements made with resistance temperature detectors, or RTDs. The application voltages at the bottom of the divider (between 6.2 V and common) set up precalibrated temperature ranges for standard 100-Ω platinum RTDs.

The auxiliary amplifier, application voltages, and 100-Ω resistor form a dynamic bridge circuit (Fig. 3). The auxiliary amplifier forces a constant 75 mV across the 100-Ω resistor. The current producing that voltage also passes through the RTD, putting a voltage across it too. The sum of these two voltages, appearing at V_X, is applied to the positive input of the signal amplifier, which compares, or sums, it with the 150-mV application voltage applied to the amplifier's negative input.

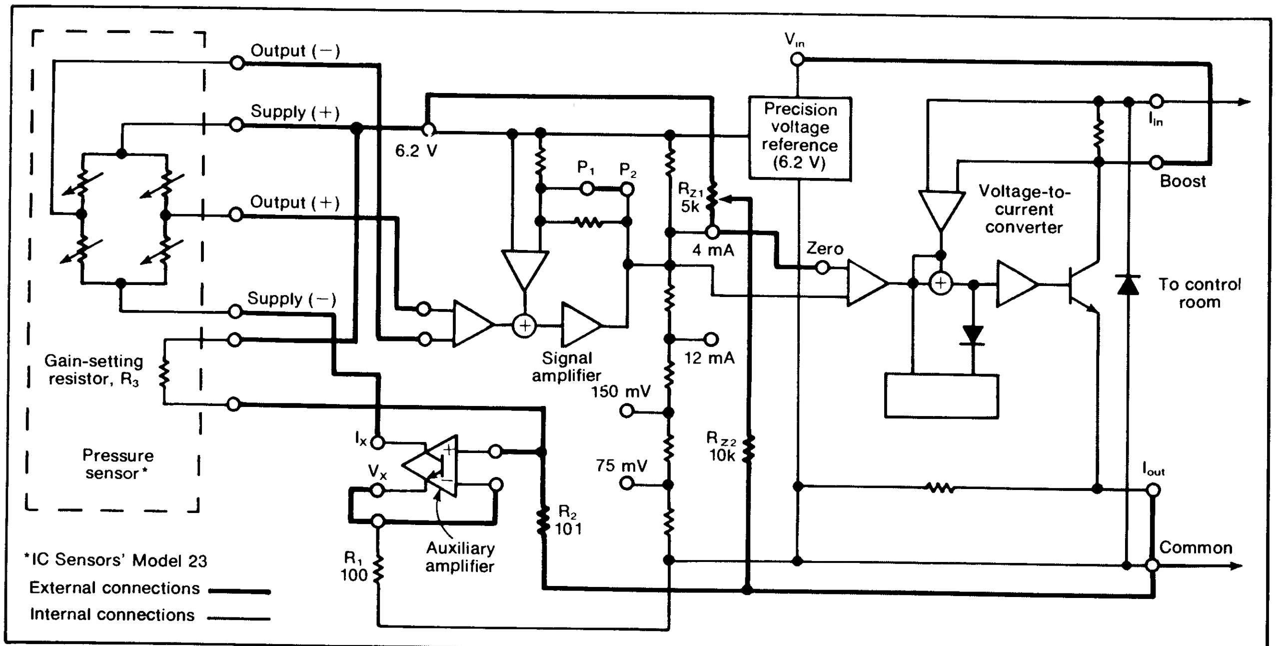
The resistance of the detector at 0°C is 100 Ω, making the voltage across it 75 mV and the output of the auxiliary amplifier 150 mV. The differential input to the signal amp is thus 0 V (150 mV−150 mV). As the temperature rises, the resistance of the sensor increases and the differential input to the signal amplifier becomes:

$$V_X - 150\,\text{mV} = (R_T - 100\,\Omega)(75\,\text{mV})/100\,\Omega$$

where R_T is the resistance of the sensor at any given temperature.

As R_T changes from 100 to 140 Ω (corresponding to a rise from 0° to +104°C), the signal amplifier's input changes from 0 to 30 mV, one of the precalibrated spans of the transmitter chip. Similarly, a temperature change from 0° to +211°C makes resistance rise from 100 to 180 Ω, resulting in a 60-mV signal—the other precalibrated span.

Other temperature ranges can be derived from various combinations of span and zero connections (see the table, p. 158). Also, still more ranges can be created by raising or lowering the application voltage—a change effected by modifying the divider, which has a nominal resistance of 1.5 kΩ at its 150-mV tap. For example, connecting a 1.5-kΩ resistor between the 150-mV tap and common doubles the resistance change required to put 30 or 60 mV into the signal am-



4. Teamed with the AD693's auxiliary amplifier, the calibration resistor (R_3) inside an IC pressure sensor can set the circuit's full-scale output span to 4 to 20 mA.

plifier and thus approximately doubles the temperature spans.

Furthermore, temperature span can be halved by doubling the gain of the signal amplifier, thereby reducing the span to 52°C. Alternatively, the application voltage can be doubled by placing a 62-kΩ resistor between the 6.2-V line and the 150-mV pin. Still other application voltages can be produced with a complete, external divider.

The AD693 easily lends itself to use with monolithic pressure sensors. For instance, it interfaces readily with the Model 23 from IC Sensors Inc. (Sunnyvale, Calif.). That sensor's internal calibration resistor makes the units interchangeable. When used with the AD693, the resistor forms part of a bias network that normalizes the full-scale output of the sensor to the 60-mV span of the transmitter (Fig. 4).

To get maximum stability over a wide temperature range, this semiconductor bridge sensor requires constant current excitation. The auxiliary amplifier in the transmitter chip is configured to deliver this current from its I_X terminals. All the current developed by voltage V_X across the chip's 100-Ω resistor is delivered through the I_X pin to the sensor. That voltage is equal to the output of the voltage divider, consisting of the sensor's calibration resistor, R_3, and a user-supplied 101-Ω resistor, R_2.

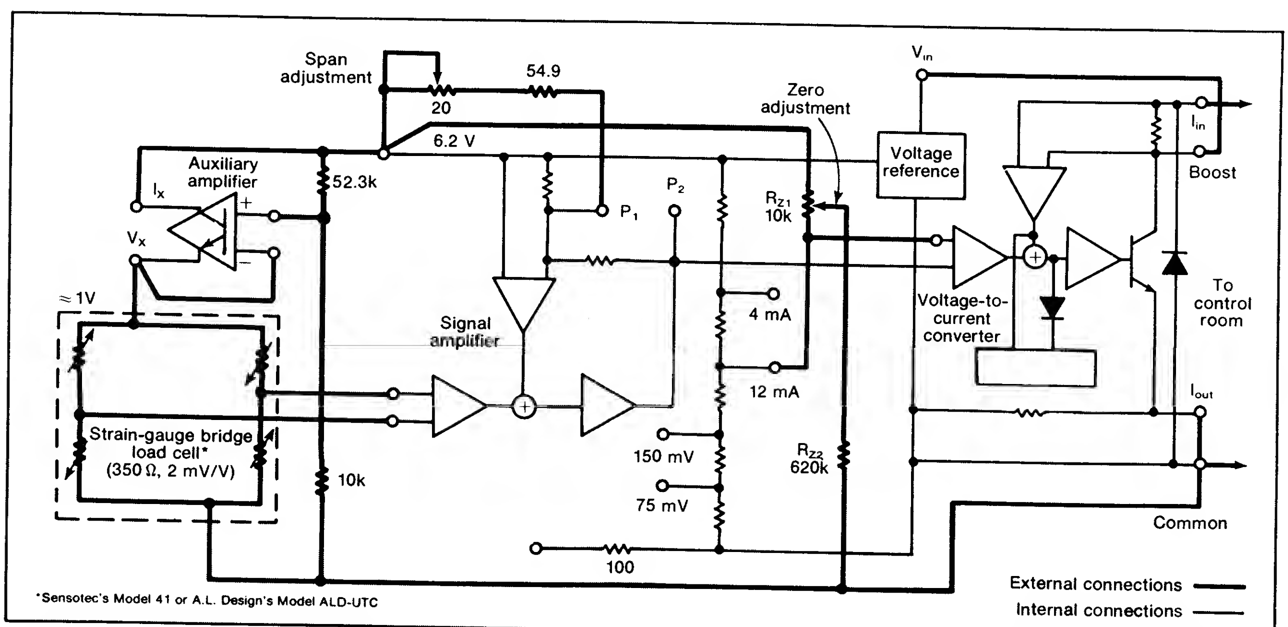
The circuit combines the preset input voltage span and the 6.2-V reference of the chip with the factory-calibrated pressure span of the transducer. Also it yields a calibrated 4-to-20-mA loop current requiring no span adjustments. Any residual zero offset in the sensor is eliminated by setting the output to 4 mA with R_{Z1}, the zero-adjustment potentiometer.

The circuit uses a Model 23-10 sensor rated at 10 psig; however, a selection of interchangeable sensors cover 5 to 250 psig. The effective span of a given sensor is halved by opening the jumper between P_1 and P_2.

If field interchangeability is not required, the same initial accuracy is available at lower cost with Series 22 sensors, which lack the factory-trimmed resistor. Instead, the user is supplied with the result of measurements of sensor output voltage at rated pressure and 1.5 mA of excitation. These sensors and similar devices from other suppliers are used in the same circuit by substituting a resistor for calibration resistor R_3. R_2 is rounded off to 100 Ω and the value of R_3 is calculated according to:

$$R_3 = [S_1\,(68\,\Omega)/\text{mV}] - 100\,\Omega$$

where S_1 is the full-scale sensor output in milli-



5. The chip's signal amplifier has enough gain to derive a 4-to-20-mA signal from the output of a foil strain gauge having 2-mV/V sensitivity. The auxiliary amplifier can be used to provide 1 V of bridge excitation, so that the bridge can be powered by the loop.

volts at an excitation of 1.5 mA. The calibration resistor normalizes the output so that the rated pressure span produces exactly 60 mV.

Load cells measure displacement of an elastic structure and the force that causes it. Metal-foil strain-gauge bridges, the most common sensing elements, are rugged, accurate, and reliable, but they are difficult to condition for 4-to-20-mA loops. Also, though they are more linear than the semiconductor units, they are much less sensitive; in addition, their usually low resistance limits the excitation voltage available from the 4-mA base-line current in the loop.

Load cells foil strain gauges

The AD693 transmitter can make the most of even that sensitivity. The internal circuitry of the chip leaves more than 3 mA of excitation current, yielding an excitation voltage of about 1 V on a typical 350-Ω bridge. The auxiliary amplifier and reference supply the excitation (Fig. 5), and the gain of the signal amplifier is raised to create a span of just 4 mV, enough to handle the typical ±2-mV/V sensitivity of the cell. (The 2-mV/V figure means 2 mV of output from the gauge for each 1 V of excitation.)

Load cells can be used in either a tension and compression mode, which produces a bipolar output, or compression only. For instance, the 12-mA tap matches bipolar tension-or-compression signals to the 4-to-20-mA span. The zero-adjustment circuit is composed of resistors R_{Z1} and R_{Z2}; the values shown in Figure 5 provide a full-scale adjustment range of ±2%.

The auxiliary amplifier, operating as a follower, provides a stiff 1 V of excitation, which may be raised to a higher voltage— thus affording greater sensitivity—if a higher resistance bridge is used. The gain of the signal amplifier is increased by placing a 54.9-Ω precision resistor in series with a 20-Ω variable resistor between P_1 and the 6.2-V line. These values derive from:

$$R_{S1} = (360\,\Omega)/[(30\,mV/S)-1]$$

where S is the required 4-mV span.